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Microphysical Fundamentals Governing Cirrus Cloud Growth: Modeling Studies

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ABSTRACT

For application to Global Climate Models, large-scale numerical models of cirrus cloud formation and maintenance need to be refined to more reliably simulate the effects and feedbacks of high level clouds. A key aspect is how ice crystal growth is initiated in cirrus, which has triggered a cloud microphysical controversy between camps either believing that heterogeneous (Detwiler 1989) or homogeneous (Sassen 1989) drop freezing is predominantly responsible for "cold" (i.e., $\lesssim -35°C$) cirrus ice crystal nucleation. In view of convincing evidence for the existence of highly supercooled cloud droplets in the middle and upper troposphere, however, we conclude that active ice nuclei are rather scarce at cirrus cloud altitudes, and so a new understanding of cirrus cloud formation is needed.

Previously, in the large-scale cirrus model of Starr and Cox (1985), for example, ice mass increases were linked to the maintenance of a relative humidity with respect to ice (RH_i) of 105%. Any growth above 105% occurred with regard to both the introduction of new crystals and the increase in mass of existing crystals, according to generalized cloud microphysical parameters. Where the cirrus cloud was absent, an RH_i of 120% was required to produce new ice crystals regardless of an understanding of ice nucleation mechanisms. The consequences of this simplified treatment cannot be evaluated without specific knowledge of cirrus ice crystal nucleation, which is considered here on the basis of detailed cloud microphysical modeling studies.

Our model, as described in Sassen and Dodd (1989), treats ice crystal nucleation and fallout in uniform 0.1-0.25 m s^{-1} updrafts embedded in a "cold" cirrostratus environment displaying vertical wind shear. Ice crystal nucleation occurs exclusively from the homogeneous freezing of haze particles composed of ammonium sulfate solutions using the freezing rate derived in Sassen and Dodd (1988) from cirrus cloud observations, which has been shown to be in good agreement with the theoretical and experimental results of Heymsfield and Sabin (1989) and DeMott (personal communication), respectively. Although the one-dimensional framework of the model limits large-scale model applications in some respects, the results are useful for comprehending basic cirrus cloud nucleation and laser scattering properties, for example (see Sassen and Dodd 1989).

A chief finding is that, even in a uniform updraft, ice particle generation in deep cirrus is accomplished in a pulse-like fashion due to the water vapor competition effects between growing haze particles and the initial ice crystals nucleated homogeneously. Figure 1 illustrates this basic characteristic in terms of relative humidity with respect to water (RH_w) and nucleated ice crystal concentrations within an impulse rising at 0.1 m s^{-1} in an environment with a 5 m s^{-1} km^{-1} wind shear. The cloud base temperature is -40°C, and the 0, 1, and 5 l^{-1} curves refer to the background ice crystal concentrations allowed to be entrained into the updraft. What is more important than the predicted frequencies of the ice generating pulses, which are influenced by the model framework, is the temperature dependency in the RH_w peaks. In particular, rather consistent results are generated over a range of likely cirrus conditions, suggesting that cirrus ice crystal nucleation occurs under reasonably predictable conditions.

The domain in the temperature/humidity field where the model simulations indicate that new cirrus ice particle generation is possible is depicted in Fig. 2. The symbols denote the results of tests using different maximum ammonium sulfate CCN masses, compared with results from basic theoretical homogeneous freezing considerations (the solid lines labeled by the CCN mass in grams). It is clear that to produce ice crystals within the homogeneous haze particle freezing regime, the required RH_w decreases with decreasing temperature, and water saturation is not required for temperatures $\lesssim$ -35°C. In effect, cold cirrus cloud processes follow an adjusted pseudoadiabat affecting fundamental thermodynamic and microphysical processes.

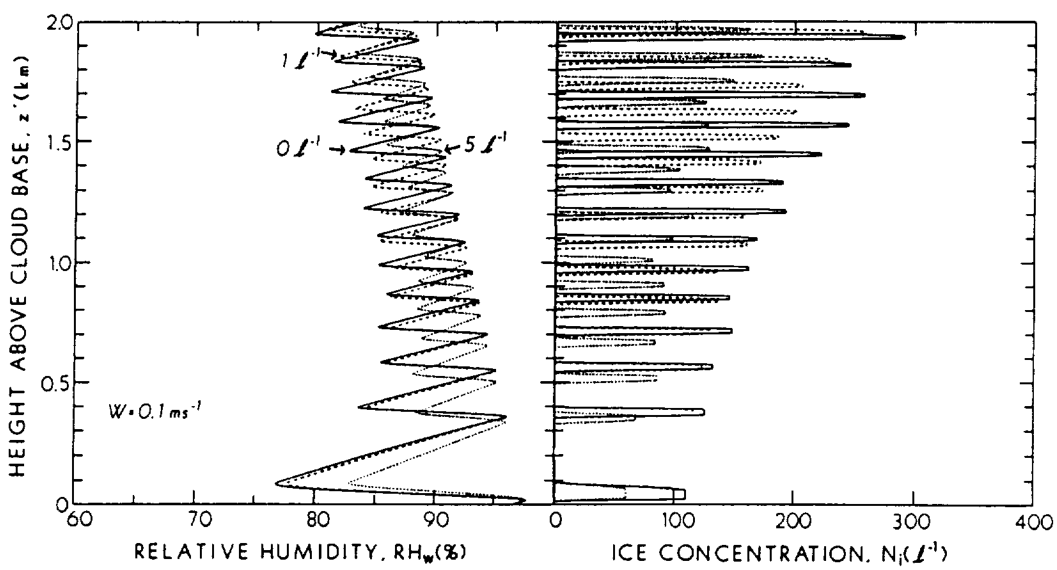

Fig. 1 Cirrus cloud microphysical model predictions of relative humidity RH_w and the concentrations of ice crystals N_i nucleated from freezing haze particles in a uniform updraft of $W = 0.1$ m s^{-1}. With increasing background crystal concentrations of 0, 1, and 5 l^{-1}, N_i in each nucleation pulse decrease due to increasing vapor competition effects between haze particles and the total number of crystals present.

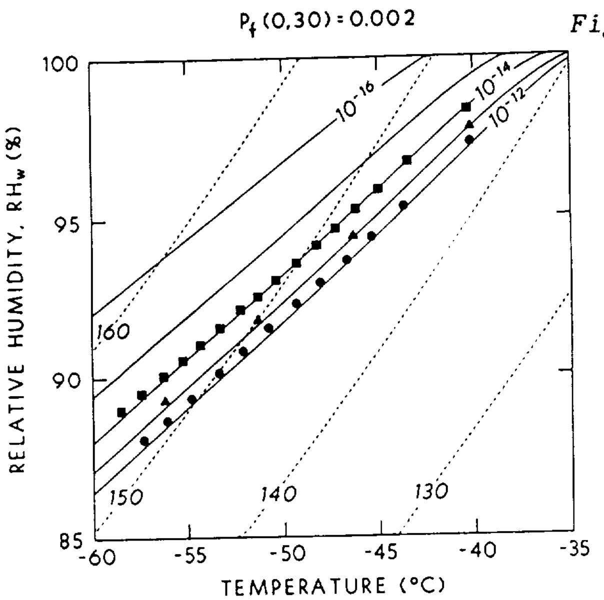

Fig. 2 *The temperature/humidity dependence of cirrus ice nucleation computed from the homogeneous nucleation rate P_f at top and on the basis of model simulations (lines and symbols, respectively). A linear fit to the "•" symbols was used for Eq. (1).*

On the basis of the model findings, we offer the following formula to describe the approximate temperature dependency in RH_w needed to introduce new ice crystals in large-scale cirrus cloud models:

$$RH_w = 5.36 \times 10^{-3}\ T(K) - 0.276 \quad . \tag{1}$$

This relation offers a considerable improvement over earlier attempts to parameterize cold cirrus cloud growth, as exemplified earlier, but at the same time further research is clearly needed to describe cirrus ice particle generation at temperatures warmer than about −35°C, where homogeneous nucleation would likely be ineffective. As a first step, however, available large-scale cirrus models should incorporate these findings to compare and evaluate the impacts of ice particle generation based on realistic microphysical considerations.

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